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Acoustic emission characterization of microcracking in laboratory-scale hydraulic fracturing tests

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ABSTRACT

Understanding microcracking near coalesced fracture generation is critically important for hydrocarbon and geothermal reservoir characterization as well as damage evaluation in civil engineering structures. Dense and sometimes random microcracking near coalesced fracture formation alters the mechanical properties of the nearby virgin material. Individual microcrack characterization is also significant in quantifying the material changes near the fracture faces (i.e. damage). Acoustic emission (AE) monitoring and analysis provide unique information regarding the microcracking process temporally, and information concerning the source characterization of individual microcracks can be extracted. In this context, laboratory hydraulic fracture tests were carried out while monitoring the AEs from several piezoelectric transducers. In-depth post-processing of the AE event data was performed for the purpose of understanding the individual source mechanisms. Several source characterization techniques including moment tensor inversion, event parametric analysis, and volumetric deformation analysis were adopted. Post-test fracture characterization through coring, slicing and micro-computed tomographic imaging was performed to determine the coalesced fracture location and structure. Distinct differences in fracture characteristics were found spatially in relation to the openhole injection interval. Individual microcrack AE analysis showed substantial energy reduction emanating spatially from the injection interval. It was quantitatively observed that the recorded AE signals provided sufficient information to generalize the damage radiating spatially away from the injection wellbore.

1. Introduction

Hydraulic fracturing in low-permeability rock is commonly used in many hydrocarbon and enhanced geothermal systems reservoirs. Throughout the fracture formation process, microcracking generally occurs in a larger region than the eventual coalesced hydraulic fracture locations. The geometry and rate of microcracking occurring during the formation of the coalesced hydraulic fracture depend greatly on the mechanical properties of the source material, the presence of discontinuities, in situ stress, loading rate, and frequency of loading (Tutuncu et al., 1998a; b). In this study, microcracking refers to the individual fractures generated at the nano- (100 nm) to micro-meter scale (100 μm), while the coalesced macrofractures are in the millimeter to centimeter scale and are the result of an agglomeration of failures. This means that microcracking in the laboratory is defined by those events readily observed with acoustic emissions (AEs) in the range of hundreds of kHz, while the macrofracturing is more easily observed with strain gages or overall sample deformation measurements. AE refers to the generation of transient elastic waves in a material caused by the sudden occurrence of fractures or frictional sliding along discontinuous surfaces (Mogi, 2007). Regardless of whether or not discontinuous features exist near hydraulic fractures, it is reasonable to expect that microcracking in the region adjacent to the fracture face will alter the mechanical responses of the material in that region. For instance, if microcracking near hydraulic fracture face is volumetric-reduction type events (i.e. pore collapse and natural fracture

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closure), the permeability in that region will be reduced consequently. Thus, characterizing the microcracking surrounding the coalesced fracture face is important in understanding the state of the damaged zone of the material prior to any production operations. This information can provide a starting point for mechanical and petrophysical property changes due to pore pressure depletion operations, rather than using original virgin material properties as the starting point for production analysis of reservoir materials.

To characterize microcracking near the coalesced fracture faces, laboratory hydraulic fracturing test was carried out while monitoring AEs on eleven piezoelectric transducers. Typically, the stress release in the form of an elastic wave is a result of permanent damage caused within the source material, such as microcrack initiation. AE source location studies have shown the staged formation of damage within a rocky material until final rupture occurs (Mogi, 1962, 2007; Lockner and Byerlee, 1977; Lockner, 1993; Rudajev et al., 2000). Specifically, AE activity has been divided into several stages by several authors and the interpretation has varied depending on the type of fracturing that is occurring as well as the boundary conditions that have been applied. Mogi (2007) described the staged AE progression as three stages throughout a rock fracture test: (i) stage A, initial stage in which no appreciable AE events occur; (ii) stage B, AE events begin to occur and their sources are distributed randomly throughout the specimen; and (iii) stage C, sources of the AE events begin to concentrate in limited regions where rupture is occurring. Although, in stage C, the AE activity typically narrows to a relatively small region of microcracking, the actual rupture takes place through this region and the individual microcrack events may or may not be directly connected to the rupture face. Fig. 1 illustrates this concept of microfracture generation throughout a continuous axial loading of an unconfined cylinder sample. The AE events shown in this figure in black color are not subdivided into particular stages, but act as snapshots in time of the accumulation of microcracks throughout a test. As seen in Fig. 1, small microcracks occurring throughout the loading and failure stages of a material oftentimes are not directly connected to the coalesced fracture, but rather occupy a damaged zone near the final fracture face. The mechanical and petrophysical responses of the material in the localized regions will differ depending on the original properties of the rock, the induced discontinuities, and the local state of stress.

To study these individual micro-failures and the possible effects they have on the rock structure, the source mechanism of the AE microcrack must be characterized. Several source characterization methods are reported in the literature including polarity distribution of first arrival signals, frequency analysis, *b*-value analysis, moment tensor inversion, and many others (Aki and Richards, 1980; Enoki and Kishi, 1998; Ohtsu, 1989; Dufumier and Rivera, 1997; Vavrycuk, 2001; Stein and Wysession, 2003; Chang and Lee, 2004; Grosse and Ohtsu, 2008). Focusing on the moment tensor inversion techniques, individual microcrack characterization was performed to obtain additional information from the microcracking process near the hydraulic fracture. The individual microcrack analysis revealed the mode of failure for the majority of the observed events. Relative volumetric deformation was characterized in two manners and was shown to exhibit large energy input in the near wellbore region. Crack displacement vector information also showed significant correlations with the principal stress directions.

2. Methods

Laboratory hydraulic fracturing test has been performed in the literature using several methodologies and analysis techniques. The following describes the theoretical background, laboratory equipment, sample material, and testing procedures of AE analyses used in this study.

2.1. Acoustic emission analysis

Although AE monitoring can, in real-time, provide useful information regarding the occurrence of impending failure of a structure, additional information can also be gained regarding the microcracking process by resolving the waveform information to account for the source characteristics of the emission events. This process is called “source characterization” and is useful in understanding the moment tensor inversion techniques (Aki and Richards, 1980). In laboratory, microcrack behavior when a material is subjected to loading conditions is focused on.

Moment tensor inversion AE can be used for the deconvolution of tensile, shear, and mixed mode events through the use of rock fracture tests. Full waveform analysis is tedious and often prohibitive due to the ability to observe hundreds and thousands of AE events in a single fracturing test. Ohtsu (1995) developed a moment tensor inversion method, known as simplified Green’s functions for moment tensor analysis (SiGMA), which simplifies the full-space Green’s functions of a homogeneous and isotropic material by only selecting the first arrival P-wave characteristics, such as amplitude, time, and polarity. By only using P-wave first motions for analysis, this procedure is capable of processing numerous events in a relatively short period of time.

Fig. 2a illustrates the fundamentals of the AE process (Ohtsu, 1995). A microcrack is nucleated along the fracture surface *F* at point *y*. The vectors in the figure represent the fracture orientation and motion mathematically, where ***n*** represents the normal vector of the internal fracturing plane and ***b*** represents the displacement discontinuity or Burgers vector. As can be interpreted, the relationship between the orientation of the displacement discontinuity

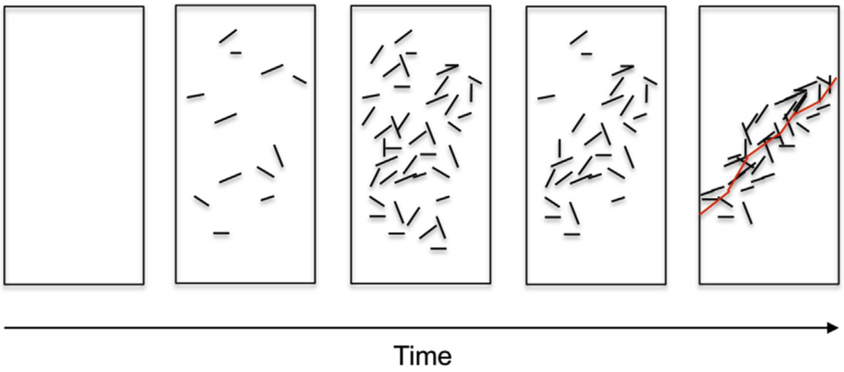

Fig. 1. Progression of microcrack sources throughout a rock fracture test and eventual fracture face shown in red color.